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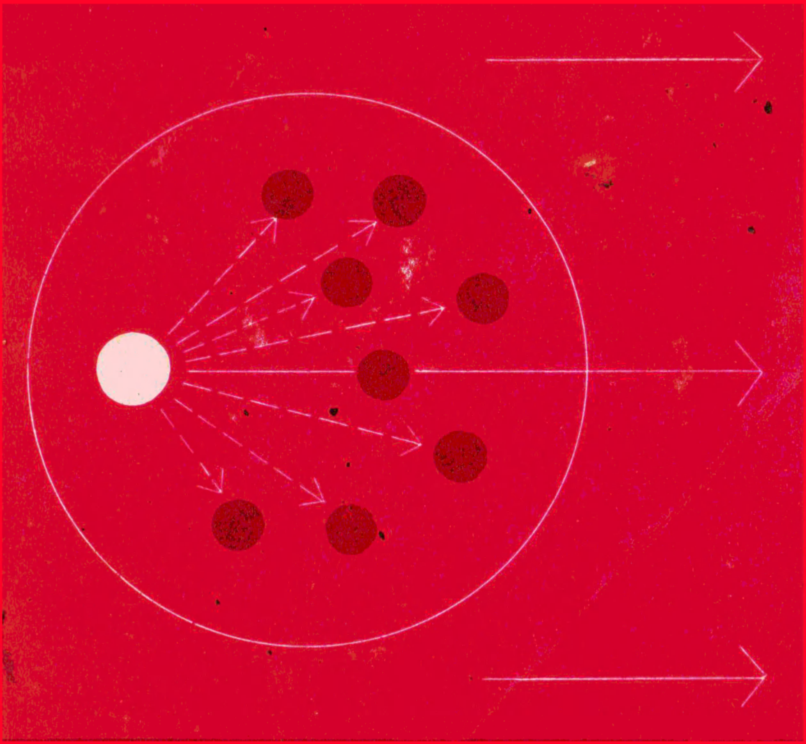
V. P. Sarantsev

Accelerators of the Future



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P. Sarantsev

Accelerators of the Future

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Contents

Principles of Particle Acceleration

The so-called *method of probe particles* suggested at the dawn of nuclear physics and used in the research of atomic objects made it possible to obtain practically all information about the atom and the atomic nucleus which we possess today. The development of the method of probe particles has led to the appearance of a new vast field – physics and technology of accelerators. It turned out that the history of nuclear physics is closely linked with the development of accelerators and all the fundamental discoveries in nuclear physics are connected in one way or another with the progress made in the technique of particle acceleration.

When first accelerators appeared 40 years ago, fundamental research began into the atomic nucleus which largely presaged the victory of man over the inter-atomic energy.

To picture the future of accelerators we must take a general look at the history of their development from a contemporary stand. This will give us an idea of the situation today and the possibilities of its future development. We shall not deal with electron accelerators but examine only heavy-particle accelerators. Electron accelerators are a sizable class of installations which are to be discussed especially.

The earliest forms of accelerators were the straight-line (or linear) ones in which particles were introduced into a static electric field and were accelerated by the field. Fig. 1 shows a schematic diagram of an accelerating tube – the main unit of such an accelerator. High-voltage, either constant, as in electrostatic generators, or pulsed, as in modern installations, was fed from a power source to region *1* shown in Fig. 1. At a high potential there was a source of ions which had to be accelerated. This potential decreased along the length of the tube and became zero at its end. The energy of accelerated particles was determined by the po-

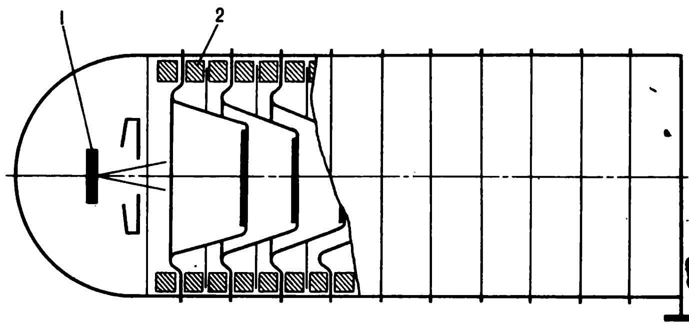

FIG. 1. Schematic diagram of an electrostatic accelerator. Ion source region *1* is at a high potential. Particles travel along the tube of the potential distribution *2* and receive an increment in energy corresponding to the total potential difference

tential difference of the power source whose magnitude was practically limited to 10 million volts. This was one of the shortcomings of this method of particle acceleration, although not the main one from the point of view of further development of accelerators. If such a notion as "particle acceleration efficiency" is introduced, meaning an increase in particle energy per unit length of the accelerating system, the linear accelerator will have the lowest efficiency. The value of a static electric field intensity in such accelerators obtained with the use of all modern technology does not exceed 10-15 kV/cm. This was due to breakdowns along the surface of a dielectric of accelerating tube *2*.

Despite their low efficiency, linear accelerators play a great role in researches even today, since accelerated beams of particles with a record low energy spread of particles can be obtained in them, the fact being rather essential for a certain type of researches into nuclear structure.

Linear accelerators had to be rejected in order to increase the acceleration efficiency and energy. The solution was quick to come: a magnetic field came to our aid. In a constant magnetic field particles of the same energy level move in a circle. When being accelerated, the particles change their circular path and begin to spiral outward.

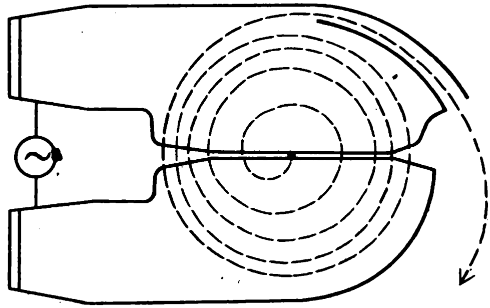

FIG. 2. Diagram and the principle of operation of a cyclotron. Dotted line shows the travel of particles in a magnetic field. They move inside a high-frequency circuit which ensures an energy increment in them

Experiments have been started to accelerate particles with the help of a magnetic field (Fig. 2). A particle moves in a magnetic field in a circle in one point of which there is an electric generator which produces not a static field but a high-frequency one. When passing through an accelerating gap of the generator, the particle is being accelerated and continues to move in the magnetic field. The potential difference, established by the moment the particle passes through the accelerating gap anew, accelerates the particle further. Such accelerators came to be called *cyclotrons*. Come to think of it, they've played a major role in nuclear physics.

Cyclotrons, too, were not free from shortcomings. In the process of acceleration, the circle, in which particles travel, increases and for the particles to be confined within the magnetic field magnets have to be really huge. Among other shortcomings there were the relativistic effects, which appeared with acceleration and disturbed the principal condition of successful acceleration – the equality of the frequency of revolution of particles and the frequency ("resonance" acceleration) of an electric generator. As a result the energy of particles obtained in cyclotrons (as compared with the energy obtained in linear accelerators) increased but a few times, while the efficiency of acceleration remained practically

the same, provided that the length of the cyclotron circumference is taken as the acceleration length.

However, from today's point of view it should be said that the introduction of a magnetic field into the cyclotron played the main role in the history of the development of accelerators. But it was not this fact alone that predetermined the major merit of cyclotrons in the development of future generations of accelerators. We shall see from the following that cyclotron (as its name implies) was the first magnetic resonance accelerator. In such a system the final energy of the particles was determined not only by the energy of the potential of the voltage being fed but also by the number of passes through the potential difference attained by the use of the alternating voltage whose frequency corresponded to the time of the particles travel in the magnetic field.

Accelerating technology developed further along the path of the improvement of this very system. But difficulties occurred along this path also. A great stride forward had to be made in understanding the acceleration process to make progress in this direction. New laws of nature had to be discovered for this step to be made. The principle of phase stability was one of them. The phase stability states that each time a particle arrives at a certain phase of the electric field (just as in a cyclotron), its movement is stable within a considerable region of phases. The deviation of particles to one side or another from the proper phase is automatically synchronized with movement and the particles tend to arrive back. Fig. 3 shows sinusoidal voltage in which particles receive resonance acceleration. Let phase *1* be the phase during which the particles pass through a voltage generator. Should a particle due to some reason or other arrive at the accelerating gap sooner, say in phase *2*, it will automatically find itself in a lower accelerating voltage V_2 and its travel in the next revolution will be slower than that of particles in phase *1*. This "wrong" particle will lag behind its phase and approach in phase the phase *1*. The picture will be the same for the particle in phase *3*. Thus, the movement in phase *1* is stable and any deviation from the stable phase will make the particle tend to arrive back.

Now, when we examine the picture of the particle movement in phase of a sinusoidal voltage, the principle of phase

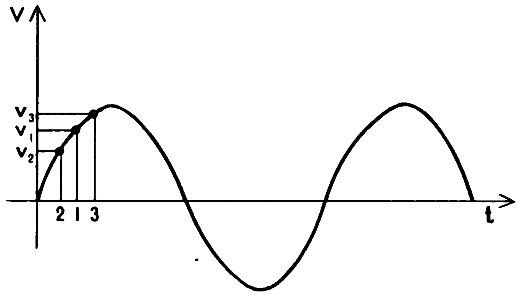

FIG. 3. Principle of phase stability in accelerators. Time *t* and voltage *V* correspond to a synchronous phase. The region bounded by points *2* and *3* any deviation of particles within which restores the particles to point *1*

stability seems to be very simple, nevertheless, in those years when a Soviet physicist V. I. Veksler came to understand it for the first time, it had made a revolution in the construction of accelerators. First of all, cyclotrons could have immediately been modernised. Phase stability allowed to use the effects, which lowered the efficiency of acceleration in cyclotrons and limited a maximum energy of accelerated particles, to stabilize the orbits of particles travel. The increment in particle mass with the increase of energy was one of the main such effects. In a cyclotron this effect led to the disturbance of the resonance acceleration due to which particles were no longer accelerated.

The principle of phase stability showed that a region of stable phases can be obtained, and, therefore, the accelerating field frequency can be varied without any fear of being knocked out of resonance acceleration provided that the acceleration phase has been chosen correctly. It turned out that the frequency change could be easily compensated for by the change in the particles' mass. Moreover, the change in frequency allowed the particles to spiral out to the field boundaries and to accelerate them as long as the magnetic field intensity holds the particles within the given radius.

The new accelerator, which came to be known as the *synchrocyclotron* or *phasotron*, created a revolution in the

nuclear experiment. The energy, to which the particles could be accelerated, and acceleration efficiency grew tenfold. Now particles could be obtained which up till now were observed only in cosmic rays. Meson physics came into being which gave birth to physics of elementary particles. Another type of accelerators – *synchrophasotrons*, which employ the phase stability principle, brought about rapid developments in this field of nuclear physics. Despite a seemingly tremendous progress which accelerators made with the design of synchrocyclotrons, the requirements of nuclear physics in greater energy grew even more rapidly.

Antiproton – a particle so well set in theoretical conceptions and offering so much new and mysterious in the experiment loomed somewhere in the offing. Everyone, the physicists including, accepted antimatter in science-fiction with due tolerance. However, any serious suggestion to obtain and accumulate antimatter in earth conditions received such a vehement and unanimous rebuff that there were very few people who ventured to speak their thoughts in public. In order to believe in "miracles" energies of particles have to be ten times greater than those produced by synchrocyclotrons of that period. Why could not a bigger synchrocyclotron have been built?

The principle of operation of a cyclotron is as such: the particles in the centre of a magnet are emitted by a special injector and then accelerated along the spiral path. In synchrocyclotrons the particles spiral out in a circle of big radius as long as the magnetic field intensity holds them in the orbit. Synchrocyclotrons 6 metres in diameter have been built. But they could accelerate protons only up to 1 GeV. With an increase in energy proportional to the radius the increase in radius would have brought about an increase in weight of the magnet as a third power of the radius. The already existing installations weighed as much as hundreds of tons. Here are the main parameters of the largest phasotron operating in the Soviet Union near Leningrad:

Magnet radius – 3.5 m
Magnet weight – 7800 t
Energy of particles – 1 GeV (1 GeV = 1000 million eV)
Acceleration efficiency – 45 MeV/m (1 MeV = 1 million eV)

One could not even dream of obtaining at such installations particles accelerated to 6 GeV (this was the threshold of antiprotons production suggested by the theory). A spiral path had to be made a complete circle. Then the magnetic field at the orbit would be quite sufficient. This would have made the magnet considerably lighter and boosted the efficiency of acceleration.

These accelerating conditions can be attained provided that time-constant acceleration is replaced by time-varying acceleration, i. e., when the electric field increases in step with the increase in the energy of the particles. It turned out that acceleration at the orbit could be ensured only if the accelerator began operating with particles which already possessed considerable energies. By that time linear accelerators appeared which were devised for preliminary acceleration of particles. The principle of operation of these machines is very much like that of a cyclotron. The only difference is that linear accelerators have no magnetic field and the acceleration is effected by a series of accelerating gaps along the straight section. This type of accelerators was also based on the principle of phase stability.

The use of special accumulators of high-frequency energy – *cavity resonators* – was a big step forward. An alternating current field wave originated in a cavity resonator by a high-frequency generator produces the so-called *standing wave*, i. e. a wave that changes only in time but not in space. The particles were accelerated in just such a wave. To make the acceleration resonant, the particles should be acted upon only in that region of the sinusoidal wave phases which originated on the basis of the phase stability principle. All other wave phases should have no effect on the particles. For this purpose, the so-called *drift tubes* were placed inside the resonator to shield the particles from the field action in the region unfavourable for them (Fig. 4).

The particles in cavity *1*, were accelerated by a high-frequency field in space *2*. During the rest of the resonator oscillation period the particles were locked in tube *3* and appeared in gap *4* exactly at the moment which corresponded to a selected phase of the accelerating field. It turned out that by varying the length of the drift tubes along the path of acceleration the particles could be resonance accelerated.

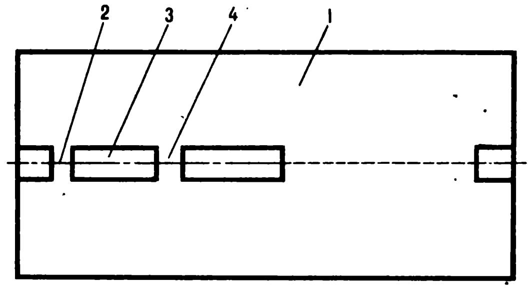

FIG. 4. Diagram of a linear accelerator. Drift tubes are placed inside a high-frequency resonator

Such an accelerator imparted the particles energies sufficient for their further acceleration with the help of the intensifying magnetic field at the orbit of constant radius. That is how a synchrophasotron or proton synchrotron, came into being, a machine that reigns supreme in science to this day.

The first synchrophasotrons resembled but very little the contemporary models although hardly two decades have passed since their appearance. The uninitiated is simply amazed at the gigantic size of the 10-GeV synchrophasotron at Dubna (this accelerator belongs to the first generation of such machines). Thirty six thousand tons of iron are positioned in a strict order along the 200-metre circumference. The particles are accelerated in the vacuum chamber inside the iron blocks. The size of the chamber – two metres across – astounds even specialists. That is what makes the magnet so heavy. The reduction in chamber size was the main trend in accelerator design in the following years. Technologically the problem, it seemed, presented no difficulties. However, the chamber size is closely related with the number of accelerated particles. Therefore, to solve the problem of diminishing its size, several highly complicated tasks had to be solved: to develop a magnetic system capable of confining in the chamber the same or a greater number of accelerated particles of an essentially smaller size.

Utterly new requirements were also demanded from the accelerator injectors.

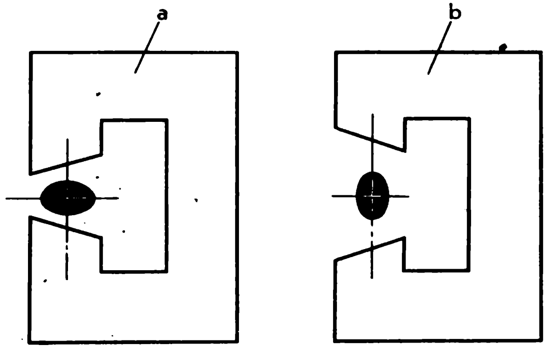

FIG. 5. The action of magnets with different pole dip on the beam of accelerated particles. Depending on the pole dip, the focusing action is either vertical or horizontal

All these problems were solved in a very short span of time and the next in size accelerator after the Dubna synchrophasotron was built along the new principles of the magnetic system design. The new principle was called "*strong*" *focusing*. Up till now, the accelerators used not a uniform magnetic field but a field which fell off radially in magnitude. Such a field permitted to maintain the particle beam during acceleration horizontally very stable. Weak change of the magnetic field was chosen because it made it possible to confine the beam both on the radius and height. If the magnetic field changes more intensively, then one of the beam dimensions decreases, and the other increases. Should the magnet be turned, its action on the beam would be reversed. This time the size that grew bigger would diminish and the other one would, on the contrary, grow. Different action of the magnet on the beam of particles, with the magnetic field either decreasing or increasing along the radius is shown in Fig. 5.

What will happen if magnets in the accelerator are constantly alternated? A great number of research works were devoted to this problem in various countries of the world. The answer was that the beam could be confined by the alternating field more strongly. At the same time the magnet chamber size could be reduced tens of times.

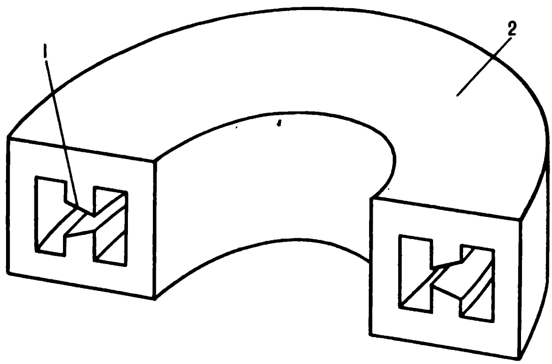

FIG. 6. Apparent cutaway of a synchrophasotron ring-shaped magnet. Large iron mass *2* enables us to set up a magnetic field of a required configuration in the region of beam *1* movement

Fig. 6 shows a cutaway view of a conventional synchrophasotron magnet. The use of inclined field poles in an electromagnet enables one to produce a radially falling-off magnetic field.

And what about the intensity? In accelerators with large chambers the particles from the accelerator-injector could be stored for many revolutions. These particles gradually filled the chamber. But the chamber became or may become too small. This called for the improvement of the injector parameters. The intensity of the injectors, as well as of the ring-shaped magnets, was mainly limited by weak transversal holding forces.

In linear accelerators the particles were confined owing to a special electric field configuration in the gap between the drift tubes. This configuration was obtained by shielding the entrance of the drift tube by special grids. But the efficiency of such focusing was evidently insufficient.

By that time there existed more effective focusing systems such as quadrupole magnetic lenses. Such lenses were placed inside the drift tubes. With the use of magnetic focusing the intensity of linear accelerators increased considerably. Thus all was ready for the birth of a more sophisticated synchrophasotron.

Before speaking about the results of incarnation of these ideas let us dwell in brief on the importance of the first synchrophasotrons, the shortcomings of which we have already mentioned. The very first synchrophasotrons made it possible to negotiate the barrier of the formation of antiprotons. Today no one would be surprised by it, since even the fact that anti-helium had been obtained at the Serpukhov accelerator hardly made a stir. Today anti-protons are obtained in impressive numbers such that special channels are being built which allow to obtain beam purity.

But, nevertheless, it is quite evident that the first experiments in obtaining anti-protons and research into its interaction with the substance have been of major importance. And although no phenomena have been found unpredicted by the theory, the very fact of obtaining an anti-proton and then an anti-neutron opened up the way towards antimatter.

Meanwhile, the accelerating technique made rapid progress; and five years after the first synchrophasotrons had been created, accelerators with "strong" focusing came into being. The first such accelerators accelerated protons to an energy of 30 000 million eV. The use of new ideas in the development of magnetic systems allowed to cut down the weight of iron yoke considerably. The path length along which particles were accelerated diminished from 2 metres to 15 centimetres. Magnetic systems permitted, in principle, to cut down these dimensions even further, but at this stage the question of accuracy prevailed. With the orbit growing steadily (in these machines it already exceeded 500 m) separate magnetic sections had to be placed with an accuracy such that the particles crossed each gap at approximately the same phase.

This is where cybernetics stepped in. Electronic computers took upon themselves the functions of adjusting the magnetic fields and correcting all troubles in them. This allowed to make yet another step in the development of accelerators. In the latest and the biggest synchrophasotron accelerating protons to an energy of 200 000 million eV (USA) the path length diminished up to 12 cm. So in this respect, too, we are approaching reasonable limits.

To illustrate progress in accelerating technology let us compare the basic characteristics of a conventional 10-GeV

synchrophasotron and those of a synchrophasotron producing particles with an energy 20 times higher.

Characteristics	10 GeV	200 GeV
Magnet diameter	72 m	2000 m
Magnet section	7.5 m × 5.3 m	0.64 × 0.33 m
Vacuum chamber section	40 × 200 cm	12.5 × 5 cm
Magnet weight	36 000 t	9000 t
Accelerating efficiency	44.2 MeV/m	31.8 MeV/m

As is evident from the table progress has been made along all the lines but one – the length of the orbit along which particles are accelerated. The length increased in step with energy. Therefore, the accelerating efficiency remained the same. This made the scientists think about further ways of accelerator development.

Was there any need for further development and, if any, then in what direction? Many important problems in physics were solved with the help of accelerators during these years, but the main problem concerning the matter structure remained to be vague. A simple model of an atomic nucleus made up of elementary particles – neutrons and protons – underwent serious changes. And the question about elementary particles has become no longer elementary. The very notion about particle elementariness disappeared after a great number of particles (their number is well beyond 100) have been discovered with the help of synchrophasotrons. Scientists were due to consider deeply the existing situation. New exquisitely-grounded theories have appeared which systematized the known particles. Sometimes these theories could correctly forecast the appearance of new particles, the fact that is decisive in the evaluation of a theory.

Another trend has come into being which asserted that the particles being observed are nothing but the manifestations of the actual elementary particles which were called *quarks*. Decisive experiments were needed to establish the truth. But the calculations showed that to obtain such an experimental results an accelerator with greater resolving power than the existing ones was required, i. e. an accelerator with greater particle energies.

They soon appeared in blueprints but their construction was delayed. If we take a look at the period following the discovery of phase stability principle we shall see that the energy of accelerators increased approximately tenfold every six years while the acceleration efficiency remained practically the same. As a result the accelerators turned into industrial jumbos.

Here are a few figures pertaining to a 200-GeV accelerator. The length of the magnet circumference (see Table) is six km. The particles are preliminary accelerated by two auxiliary accelerators: by a linear one – to an energy of 200 MeV and by a synchrophasotron – to 8 GeV. (This synchrophasotron is practically similar to one of the first synchrophasotrons at Dubna.) The entire accelerator unit costs 250 million dollars. Therefore, the next energy jump will cost 1000 million rubles. This huge cost made physicists think how to boost the acceleration efficiency, and, consequently, to cut the expenditures.

At present we see three main ways which allow us to hope that in the nearest future a new step will be made towards the improvement of the accelerator efficiency.

First of all, opposed beams is a relatively old line of development. Its appearance can probably be referred back to mid-50's when a possibility of accumulating accelerated particles in a constant magnetic field was demonstrated. At the time, the very suggestion avoked heated discussions. Even venerable physicists who did a great deal for the development of new accelerators could not reconcile themselves with the new idea. It seemed so far that it was impossible to accumulate particles in a magnetic field permanent in time, that it simply contradicted the basic laws on which the accelerator design was generally based. It turned out that there was no contradiction at all. The question was how to inject particles into a magnetic field.

Let us look into the advantages of this method. This is approximately how micro-objects are studied with the help of an accelerator. A beam of accelerated particles is directed to a target; and then the reaction products obtained as a result of interaction of the particles with the target nucleon or with the nucleus as a whole are studied. Consequently, what is important is the result of the interaction of the two

particles. It is known that the interaction characteristics are usually given in the centre of mass of the interacting particles. Thus different characteristics are obtained when flying particles interact with a fixed target and when two particles fly head-on. The interaction of the latter is equivalent to the interaction of particles of a considerably greater energy with a fixed target.

Naturally, a question arises: how the development of the possibility of accumulating particles in a constant magnetic field is related to the realization of opposed beams? Most directly. The idea of using opposed beams is an old one, but its realization was regarded doubtful since calculations showed that single collisions of two beams produced a very small interaction effect, such that physical apparatus failed to register it with certainty. Accumulation allowed to boost the intensity in the particles considerably and make use of multiple interaction of two beams. The construction of electronic models of such accelerators was immediately started at which not only this method was substantiated but also physical results pertaining to scattering of electrons on electrons have been obtained. These experiments gave birth to an idea of using the new method for studying the structure of the proton. Today this idea came into being; two intersecting magnetic accumulating rings have been built in a 30-GeV accelerator. At recent conferences the first results of the interaction of particles with energies equivalent to those obtained at conventional accelerators with energies of particles exceeding 1000 GeV were declared.

These results were so impressive that all the projects of the new accelerators are being oriented, to a certain degree, at the possibility of counter impacts of particle beams. To make such an installation a multipurpose one, it is envisaged to make different particles collide. The installation, as the theoreticians think, should have five intersecting rings containing different high-energy particles such as protons, antiprotons, electrons, positrons and mesons. The installation should enable these particles to collide.

It seemed the problem was withdrawn – a method was found to overcome the barriers in the energy of accelerated particles. But it appeared that not in all interactions the initial beams were equivalent to the accelerators with fixed targets.

Such a fixed target as an opposed beam with a low-density substance allows to conduct only certain experiments which cannot answer all theoretical questions. Again the question of developing a large accelerator with higher accelerating efficiency arose.

Perhaps, this effect could be obtained in the same synchrophasotron? The only way, it seemed, was to increase the magnetic field. But it could not have been done in iron magnets. That was when the scientists turned to superconductivity.

Superconductivity – the decrease in resistance of certain materials as their temperature is reduced to nearly absolute zero – is something that gives no peace either to physicists or to engineers for many years running. It promises simply breath-taking perspectives in energetics. But at the same time it is also the most striking demonstration of the fact that nature does not yield its secrets without struggle. We observe this anomaly in conductivity only at temperatures of liquid helium and it is far more difficult to contain helium in a liquid state than any other gas. The last few decades were devoted to helium "harnessing". Today, it seems, we can say that all the efforts were not in vain: the experiments entered the stage of technological incarnation. The properties of superconductors exhibiting superconductivity at low temperatures were used to obtain magnetic fields of high intensity. The employment of superconductors made it possible to obtain in conventional solenoids magnetic fields with an intensity ranging from 50 000 to 70 000 oersteds.

You may ask why their intensities were so low, when higher field strengths were expected?

It turned out that the magnetic field itself had a destructive effect on a superconductor. At a certain field value – it was called critical – a superconductor became an ordinary conductor. However, even such field values transferred to an accelerator promised substantial gains. But simple transfer was impossible. Superconductive devices operate on direct current, while in synchrophasotrons the current should be changed during acceleration in accordance with a definite law. The ohmic resistance in a superconductor is nearly absolute zero. If such a conductor is placed in an alternating magnetic flux, eddy currents will be induced in it just as in any other

metal with the only difference that in a conventional metal these currents attenuate due to ohmic resistance, while in a superconductor they are being gradually accumulated. At certain current values the magnetic field becomes so intense that it brings the superconductor out of the state of superconductivity. This transition may lead to a rapid heat evolution which at temperatures of liquid helium may cause a lot of troubles. This is one side of the question. And the other one, to my mind the most important one, is the supplying losses at the initial stage of the process described above. These losses have to be met by an increased flow of liquid helium, a process that demands today considerable expenses, i. e. costs quite a penny. In order to have an idea about the cost of the corresponding losses at helium temperature we shall cite only one figure: it costs nearly 500 000 rubles to compensate for just one kilowatt of losses at low temperatures. This figure includes only the cost of a refrigerator unit which can produce the given amount of liquid helium.

Naturally, in order to think about an accelerator with a superconductive magnet a start should have been made of creating a superconductor with low losses. This demanded superconductors with small cross sections. The experiments that followed showed that it did not tackle the problem. Magnets need conductors with heavy current and, therefore, superconductors should have large cross sections. If thin wires are bunched then we have to deal with a total cross section much greater than that of a single wire. To design very first pulse magnets physicists had to show so much ingenuity that it could only amaze one. In one of the well-known institutes to make a superconducting cable a hosiery machine was used with the help of which a 10-mm stocking was knitted from thin wires and which was used for the magnet design.

The very first experiments showed that a pulse iron-free magnet could, in principle, be designed, but long and complicated work of technological processing of superconducting cables had to be done to make the time rise of a magnetic field comparable with the time rise (of the order of a second) characteristic for the accelerators with an iron magnet.

About four years passed after the first experiments with pulse magnets had been conducted, but the progress made is

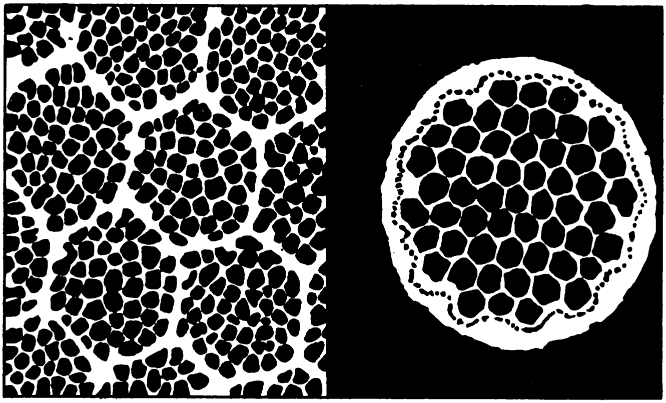

FIG. 7. Cutaway view of the superconducting cable at different magnifications. On the left is shown a more fine structure of separate groups of superconductors

trully startling. We already have such cables now. They are very complicated in structure. Imagine ten thousands of superconducting wires about a micron thick, each of which is coated with a copper film to prevent catastrophic evolution of heat in case the superconductivity is violated. The conductors are combined in several tens of groups in a strict order. Each group turns or changes its position in the cable cross section depending on its length according to a definite law. And all these combinations of conductors are incased in another copper sheath (Fig. 7).

But the design of such cables did not solve the problem of building accelerators as such. A number of questions have to be solved both of purely technical (for instance, what is the most advantageous configuration of winding) and of physical nature (for instance, what magnitudes of a residual field due to excitation currents in superconductors should be taken into account; is this field uniform, and does it retain its magnitude at various pulses?). You cannot even speak about the superconducting accelerator without answering these questions.

In recent years experiments have been made in many countries on selecting the configuration of superconducting

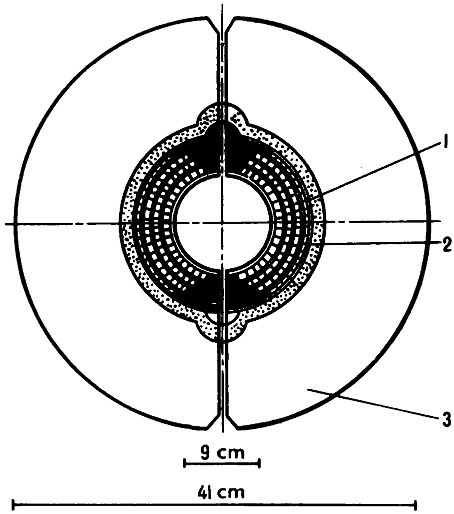

FIG. 8. Section of a specific superconducting magnet. A special winding of superconducting cables *1*, *2* permits to obtain the field of a required configuration. All the superconducting windings are housed in iron yoke *3*

windings required for an accelerator. They showed that the winding system inside the iron shield evidently had the least number of shortcomings. One of the variants of such a magnet is shown in Fig. 8.

What are the advantages that superconductivity promises to accelerators? Recently conducted experiments showed that the magnetic field can be increased almost threefold. The acceleration efficiency will also increase as much. Here are the concrete data pertaining to one of these superconducting systems. Let us examine one of the latest designs of a 200-GeV superconducting accelerator. If we consider the table demonstrating the data for an accelerator of the same energy using a conventional iron we shall easily see the difference. Here are the basic parameters of the superconducting accelerator:

Orbit length – 2000 m
Maximum field – 40 kgf
Acceleration efficiency – 100 MeV/m

Comparison of the accelerator costs shows that transition to superconducting systems makes them 2 to 2.5 times cheeper. These evaluations were made for a definite type of a superconductor – niobium-titanium one. Today we already know superconductors which in principle can increase several times the above-cited figures for the field value. But so far we do not know how to use such superconductors in the pulse duty.

While discussing superconductivity and its effect on the accelerator development we must touch on the problem of superconducting high-frequency cavities. The solution of this problem would mean a big stride forward in increasing the efficiency of linear accelerators. In building such accelerators main expenditures are connected with large amounts of power of the high-frequency systems required for excitation of accelerating cavities. Low acceleration efficiency leads to lengthening of accelerators.

Both these problems can be solved by using superconducting elements. Hence, the great interest in them. Much research in this field was devoted to the solution of these two basic problems of superconducting cavities – obtaining of high values of the quality factor (low losses) and of high electric field intensities. The first problem received prime attention and a certain progress has been made in its solution.

Conventional cavities have a quality factor ranging from 1000 to 100 000, i. e., cavity oscillations attenuate at 1000 to 100 000 swings. Today the quality factor obtained at superconducting cavities is as much as 100 000 million.

However, today when such a progress has, seemingly, been reached and the problem has been all but solved much pessimism is being voiced in respect of the practical use of these achievements. There are serious grounds for this pessimism. Firstly, the technology of manufacturing the cavities and processing their surfaces is so complicated that they cannot be mass-produced. But the cavities with high quality factor cannot be used to increase the electric field intensity but they even reduce its values as compared with the cavities without superconductive systems.

The last years of researches were directed at the elimination of this very shortcoming. A compromise decision was arrived at which permitted to start designing the first

accelerating sections. It was decided to give up high quality factors, temporarily I hope, and to be satisfied with 10-100 times lesser values. This simplified the production process of cavities and improved their characteristics from the point of view of obtaining high electric field intensities. This research work made hopes of creating superconducting linear accelerators real. Today it is still too early to speak about raising the acceleration efficiency in such systems, and it would hardly be considerably higher than in the first accelerators.

Finally, there is one more possible way of accelerator development: the use of the so-called *collective phenomena* for particle acceleration. This is a completely new approach to the problem of particle acceleration differing from the one we discussed above. In recent years a substantial progress has been made in this direction and it seems that this approach has won its right to exist along with the others. Let us dwell in detail on the basic principles of the new method and try to evaluate its future possibilities.

The first suggestions on the use of the new effects for particle acceleration date back to 1956. The ideas suggested were so unusual for specialists working with accelerators that even the most prominent of them could not at the time fathom all the possibilities contained in them and regarded these ideas as a flight of imagination. The remarks would have been more poisonous if not for the prestrige of the scientists who had formulated them for the first time. These ideas belonged to prominent physicists – V. I. Veksler, who put forward the principle of phase stability, Ya. B. Feinberg and G. I. Budker.

Let us consider each of these three new suggestions. We hope the reader shall not be disappointed if he notices that some of them have not yet been realized in the accelerating techniques. The thing is that the interference of these suggestions is so great that if there is a progress in any one of the directions it is inevitably linked with a high level of understanding of the processes which have been attained as a result of the research into all the three directions.

I think Budker's suggestion had the greatest impression on specialists, particularly young specialists, for it opened a real perspective to go over to particles with energies of 100 GeV

on the basis of a conventional betatron one metre in size. Such energies were attained while in Dubna the 10-GeV synchrophasotron was only in the process of construction and the principle of strong focusing was not formulated yet. The reader shall agree that this was on a par with a scientific and technological revolution in accelerator building.

What were the main ideas behind such a suggestion? We must introduce here certain basic quantities characterising an electron beam because without them it will be rather difficult to explain the principles of the new idea.

Usually for relativistic movements (movements with velocities of the order of the velocity of light) the notion of velocity is replaced by the ratio of the velocity to that of light and is denoted by β. A somewhat different characteristic is used to denote energy. In the relativity theory there is such a notion as rest energy. In accordance with the relativity theory in moving bodies the mass increases in step with the increase in their energy. It is more convenient to denote energy in rest energy units. This relation is designated by symbol γ. Now about the essence of this suggestion.

The example of the magnetic field of a synchrophasotron showed us that this field, in addition to ordinary functions of keeping the orbit of the particles movement within the given circumference, has another no less important functions of confining the beam transversally. These last functions demand a rather strict limitations from the shape of the magnetic fields which can be used in the accelerators.

Actually Budker's suggestion boiled down to the fact that the external field performed only one function – the function of confining the beam radius and not of the entire beam but of only one of its components. The beam could independently remain stable. The beam was able to maintain its cross section. But the beam, which was called the relativistic stabilized electron beam, was an unusual one. It was an intense electron beam possessing certain properties, its charge being fully or partially compensated by ions. W. Bennett, a well-known American physicist, pointed to the possibility of its existence as far back as 1934.

Let us consider such a beam. It turned out to be of importance for the collective methods of acceleration. Imagine

two electrons in certain two points in space. As the electrons are charged, an electric field sets in between them in accordance with the laws of physics. Since the charges are like the field repells them. This force came to be known as the *Coulomb force*. The situation changes somewhat if the electrons move parallel to each other. The Coulomb force continues to act just as it did in the case with particles at rest, but there also arises another force – a magnetic force. The moving charge, in this case it is an electron, is an electric current. An electric current is surrounded by a magnetic field. Magnetic fields from two moving electrons interact with each other. The force of interaction is directed opposite to the Coulomb force. Therefore, for two moving charges the repulsion force decreases.

It appears that the force of interaction depends on the energy of electrons and decreases as compared with the interaction of electrons at rest as γ^2. In order to get accustomed to the terms introduced, let us consider a simple example. Let the moving electrons have an energy of 10 MeV. The rest energy of an electron is 0.5 MeV, i. e. $\bar{\gamma}=20$. Therefore, the repulsion force for such electrons is 400 times smaller than for electrons at rest. What is good for two electrons is also valid for a beam of electrons. We have arrived at a conclusion that the repulsion force for a beam of relativistic electrons is essentially weakened.

To eliminate the repulsion forces alltogether we shall introduce ions into such a beam. Ions are positively charged and the field that arises between the ions and electrons is such that these particles are attracted. Since the charges of ions and electrons are equal in magnitude it would be enough for the above example to add 1/400 of the number of electrons to set the equilibrium.

What will happen if the number of ions continues to increase? Then the Coulomb repulsion force will be replaced by the force of attraction, i. e., the magnetic field begins to prevail over the Coulomb forces. If the current of electrons in a beam is sufficiently large, say of the order of 1000 A, the magnetic compression is quite great. Strong compression leads to energetic lateral electron oscillations in a beam which results in energy evolution; as a result the lateral movement is damped and the beam contracts into a thin cord with

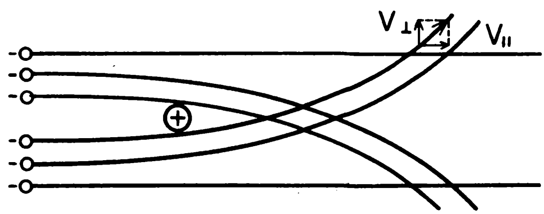

FIG. 9. Diagram of interaction of a beam of electrons with an ion. In the final analysis such an interaction increases the transverse speed of electrons

huge electric and magnetic fields. It is these fields that according to Budker will confine the beam transversally.

But is there a limit to such a compression – may this process continue for ever? It appears not. The process which prevents the beam from being compressed infinitely is connected with the scattering of electrons on ions located in the beam. Imagine a beam of electrons passing near the ion. Assume that all electrons had parallel speeds before they encountered with it; lateral components were absent completely. On passing near the ion electrons come under the action of the Coulomb forces (Fig. 9). As a result their paths curve and speed lateral components appear, in other words, the beam grows in size. The beam growth generates radiation and dynamic equilibrium is established under the effect of these two factors. Naturally the question arises how quickly this equilibrium can be established? How much time does it take for the stabilized dimensions to be established and what are the dimensions? For the fantastic for those times electron currents of the order of 10 000 A time was estimated in seconds. Electrons in this insignificant span of time traversed fantastic distances (speed about 300 000 km/s), hence the realization of Bennett's suggestions would require cosmic space.

Soon everyone forgot about that; and it was only 20 years later that Budker declared from the podium of the conference on accelerators that in earth conditions we can only speak about a closed stabilized beam – a beam which has the form of a ring. For this purpose it should be placed in a special magnetic field of a definite shape, similar to that of a [illegible]

tron. As distinct from the conventional betatron, the intrinsic or internal magnetic field of the beam is much larger than the external one. Configuration of the intrinsic fields allows to use the space inside the beam for ion acceleration, the accelerated ions being confined at the orbit and focussed due to electric and magnetic intrinsic fields of the beam. The external field only moves the electrons to an orbit and, therefore, it can be of a moderate size.

To substantiate these complex calculations made for this rather unusual system, an example has been given of obtaining an equilibrium for the beam of electrons in a betatron with an energy equal to 15 MeV, with an electron current equal to 1000 A. The state of equilibrium for such a beam set in with the beam radius equal to 4×10^{-2} mm. In the process a magnetic field equal to 50 000 gausses arose at the beam surface, while the external field, the betatron field, being one metre in radius, amounted to about 1350 gausses.

On the basis of these calculations it was suggested to build a 100-GeV accelerator within the limits of a conventional betatron.

Experiments were started to put this principle of ion acceleration into practice. It appeared that as the best electronic accelerators produced currents of a few amperes, it was only G. I. Budker, a man of wonderful talent of the inventor with his vastless fantasy, who could undertake the development of such an accelerator. His very first experiments resulted in a production of a 100-A electron current in a betatron. Experience, however, showed that the beam sections were too large – several centimetres – while the time required for setting in the equilibrium approached several minutes. During this time the beam itself deforms considerably. The thing is that the experiments were conducted in a vacuum chamber at a pressure of 10^{-6} mm of mercury column. At such a pressure the number of atoms of a residual gas is still great and the electrons, while ionising this gas, captured a great number of ions such that their number exceeded the number of electrons. There was nothing to confine such a number of ions and the beam just ceased to exist.

Regretfully, these experiments were stopped mainly because Budker with his enthusiasm took up the problem of the opposed

beams and brilliantly solved it. It must be said that probably today as never before physics came closest to resolving the problem of a self-focusing beam. It approached this problem from two different standpoints: from the point of view of heavy-current electron beams and from the point of view of obtaining a ring bunches for other types of collective accelerators. We shall dwell on it later on.

The ideas of Ya. B. Feinberg formulated by him for the first time in approximately the same period related to the possibility of accelerating particles in plasma by special electromagnetic waves. Such a wave could have been excited in plasma by an external source of electromagnetic oscillations, and the entire acceleration system was named "plasma waveguide".

But waveguides, to hold true, conventional but not plasma, have already been used in accelerators. And what are the advantages of plasma waveguides over conventional ones? Conventional waveguides from the point of view of their use in accelerating machines have, I think, two serious drawbacks.

The first and the main one is their relatively low accelerating efficiency – 5-10 MeV/m, which in a linear accelerator simply coincides with the electric field intensity. This is due to the fact that the so-called *cold breakdown* occurs at high values of the electric field. Even if methods of overcoming these unpleasant phenomena were found, it would be impossible to increase the field intensity essentially, because for this purpose too much great fluxes of electromagnetic energy would have to be passed through a waveguide system.

Thus, if we imagine a tenfold increase of field intensity, then high-frequency energy losses in such an accelerator would amount to 200-300 million W/m of the system length. Such great losses are due to the field intensity set up in the waveguide.

Moreover, the conductivity of the waveguide metal walls is also responsible for the losses. If we take a deeper look into the process of losses, the waveguide conductivity is directly connected with the frequency of particle collisions inside the walls of a waveguide. This value for the wavelengths usually used in waveguide accelerators depends but little on the material the waveguide walls are made from.

The transition to superconducting waveguides could have been one of the possible variants of the solution of this problem. Ya. B. Feinberg suggested an entirely new approach – to reject metal waveguides in favour of a low-loss medium, plasma in particular.

Why, you may ask, has such an exotic material been chosen? When we discussed the principle of operation of linear accelerators, we said that the electromagnetic field in them provided only longitudinal movement, while radial stability of the beam is achieved with the help of focusing lenses. The field alone cannot confine the beam effectively.

A group of physicists-theoreticians headed by Ya. B. Feinberg demonstrated that when an electromagnetic wave is propagated in plasma the conditions of both longitudinal and radial stability could be satisfied. As distinct from metal waveguides in which the waves propagate in a vacuum and the waveguide properties are determined by reflection from metal surfaces, in most plasma waveguides the waves propagate in plasma itself. The possibility of making use of such waveguides for particle acceleration is based on the fact that micro-radio waves show their waveguide properties already at low densities of the material. The density of electrons in a metal is tens of times greater than that which is required for ensuring waveguide properties.

And it is exactly this great density of particles that is mainly responsible for the energy losses in the walls of a waveguide. The density of plasma can be varied and it is possible to find such a compromise when the wave will be propagated in the plasma with low losses. But moreover, plasma possesses heterogeneous electric properties. Its dielectric properties may differ in lengthwise and crosswise wave travel, and it is they that determine the stability in particle acceleration. It has already been shown that all the necessary conditions for particle acceleration could be created in plasma. Thus a waveguide of quite a new type appeared in which field intensity can be raised considerably. Actually it was shown that even at relatively low densities wave intensity in plasma reaches million volts per centimetre.

The designers of this accelerator had to solve one of the most important questions of how to excite in plasma electromagnetic waves necessary for particle acceleration. An

extensive research work conducted along these lines revealed that the excitation of longitudinal waves in plasma with the help of an electron beam is the most effective today.

The electron beam passing through plasma interacts with electrons in it and, as a result, definite conditions being observed, an electromagnetic wave begins to propagate along the beam travel, the efficiency of transmission of the beam energy to this wave being relatively high – of the order of 30 per cent of the total beam energy.

Such experiments were at first conducted with low-current beams – of the order of tens of kilowatts and in the following years the transmitted power already reached tens of megawatts.

The most essential conclusion drawn from these experiments is the independence of a fraction of the energy being transmitted from the total energy of the electron beam. This gives us grounds to hope that when operating with more powerful beams (and we already have such beams) we shall be able to obtain such waveguides with a record field intensity. However, not all kinds of longitudinal waves may suit particle acceleration. We must select a wave with a fixed frequency which would travel at a preset phase speed, in other words, it is required to be able to control the process of wave formation in plasma.

The very first experiments showed that the excitation spectrum of oscillations is quite broad. It was necessary to disturb the phasing of particles in a beam for the oscillations, the frequency and wavelength of which differed from the preset ones, and to intensify the phasing control at the selected wavelength.

This problem had, as is often the case, a very simple solution. What if the beam is modulated at a preset frequency? In theory the spectrum of oscillations around the selected modulation frequency constricted considerably. The experiment proved these theoretical conclusions. Already in the first experiments the half width of the oscillation spectrum in plasma reduced from 70 to 3 MHz. What remained to find out was whether the excited wave had regular phases of oscillations in length or whether they were accidental. It turned out that beam modulation played a positive role – it made oscillations regular.

Thus a wide range of problems was solved and it seemed that one more step had to be made to make the development of accelerators with higher acceleration efficiency possible.

These experiments in studying the interaction of the beam with plasma were also of great importance because they inaugurated yet another trend in development of accelerators. At the end of the 1950's the workers of the Sukhumi physico-technological institute were engaged in the research of possibilities of obtaining heavy-current electron beams from a plasma source. They discovered that under definite conditions plasma ions were observed with energies essentially surpassing the potential difference applied. Thus to obtain electrons, the voltage of the order of 100 kV was applied to a source, while ions had energies of several million of electron-volts. A limited amount of plasma and insufficient duration of the process made further research into a new phenomenon difficult.

Consequent tempestuous development of heavy-current electronic accelerators allowed to launch a detailed study of the mechanism of direct energy transfer from the electron beam to plasma ions. However, we still are unable to control this process, although there are grounds to hope that in the near two or three years such a method will allow us to obtain great ion fluxes of not very high energies. Today, the accelerating field intensities reach about one million volts per centimetre.

Finally, we must dwell in more detail on the method of particle acceleration which has received the greatest development. Unlike all the previous methods, this method is a versatile one. Today we can already not only speak about raising the efficiency of particle acceleration but also suggest concrete circuits of accelerators for high energies, for medium energies with increased intensity as well as for accelerators of heavy ions.

The new method has undergone essential changes in the process of development, therefore we have to dwell on its certain stages in more detail. Firstly, we must note the first suggestions of V. I. Veksler which he voiced in mid-50's. The new principle of acceleration was called *coherent*. Characteristic of this method is that the electric field which accelerates the particles is not an external one but appears

as a result of the interaction of a group of accelerated particles small in its geometrical dimensions with another group of charges, plasma or with an electromagnetic wave. In such a method, the smallness of geometrical dimensions is of principal importance, since if these dimensions are small enough, all the accelerated particles would participate in the creation of the accelerating field and the field value turns out to be proportional to the number of these particles.

This field is induced only in that spot in space where there are accelerated particles and the synchronism of acceleration is ensured automatically. V. I. Veksler examined three variants of the development of such an accelerator – acceleration by media, impact coherent acceleration and radiation acceleration of plasma bunches.

Acceleration of Charged Particles by the Medium

It has long been known that charged particles, moving in a medium, spend their energy on the so-called *Cerenkov radiation*. The use of this phenomenon allowed to build a whole family of particle detectors. Later on I. E. Tamm demonstrated that particle losses in radiation can be recompensated, in other words, if a medium, moving at a high speed, flows around a charged particle then part of its energy has to be imparted to the particle at least as long as the speed of the medium and that of the particle will not be equal.

V. I. Veksler pointed at the possibility of the practical use of this effect. Actually, if a high-energy electron beam with a great density is used as an accelerating medium, ions can be accelerated in it by making use of the reversibility principle of the Cerenkov effect. The magnitude of the accelerating field acting on an ion is therewith extremely small. That's exactly where radiation coherency came into force.

It is a fact that energy losses in the Cerenkov radiation are proportional to the square of the charge. The reversed field is also dependent on the charge. Therefore, if an electron medium interacts with a bunch of ions sufficiently small geometrically and with the number of charges equal to N, the force acting on a separate particle may be increased N times. This is accounted for by the fact that, as was shown above, every ion, while interacting with a beam of electrons, excites in it an electromagnetic wave.

If an ion bunch is small as compared with the wavelength of this disturbance, then the disturbances from all ions may be added up and as a result an electric field proportional to the number of accelerated ions sets in.

V. I. Veksler's theoretical evaluations showed that in such acceleration the accelerating fields of millions of volts per

centimetre can be obtained. In this process the second main problem of the accelerating technology is being solved – that of obtaining high intensity since to obtain high field intensities an accelerated bunch should have a great number of particles. The practical solution of this problem, however, demanded the solution of a complex problem of retaining the bunch size in the accelerating process, in other words, the problem of stability. While transversal stability could have been ensured owing to a charge carried by an electron beam, longitudinal stability could not be ensured. That meant that in the process of acceleration the ion bunch smeared, the conditions of coherency were no longer kept and the accelerating fields lost their intensity.

Before we speak about the paths of the solution of this problem let us dwell on other Veksler's suggestions because they were concerned with other similar problems.

Impact Coherent Acceleration

The previous suggestion was formulated in the years when it was technically impossible to obtain electron fluxes of high density, therefore, the author gives it a modest place in the accelerating world. V. I. Veksler hoped that the intense ion beams of moderate energies could be obtained by this method.

To obtain ions accelerated to maximum high energies, V. I. Veksler suggested another variant of coherent acceleration – *impact coherent acceleration.*

Let us picture the mechanism of such an acceleration, first, two interacting particles taking as an example. Let the particle with mass M_1, moving with a great speed so that its energy in the value of the rest energy is equal to γ, collide with another particle with mass m_2, considerably smaller than the mass of the first particle. If the collision was head-on, then the particle at rest will attain a very great energy already proportional to γ^2.

To explain high efficiency of the acceleration, let us examine a simplified diagram of such an impact (Fig. 10). The given diagram does not in fact represent a precise picture but nevertheless it gives a relatively correct understanding of the phenomenon.

Let us examine the three phases of particle interaction. The first phase is known: particle M_1 moves with an energy γ, particle m_2 is at rest. The next phase is similar

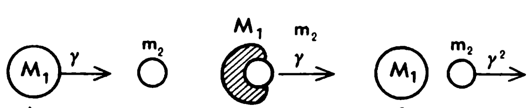

FIG. 10. Three phases of interaction of two charged bunches illustrating impact particle acceleration

to the first method of acceleration, discussed above, when the medium, a heavy particle in this case, entrains the other one. The only difference is that both bunches are compact; in addition to an ordinary entrainment of particle the Coulomb field loses its shape.

The state of equilibrium sets in when the force of entrainment acting upon particle m_2 is compensated by the Coulomb force. This equilibrium persists until the speeds of the particles become equal. The entrainment force becomes zero and the system is no longer in the state of equilibrium. In the third phase the Coulomb forces reject particle m_2, thus increasing its energy γ times. Hence, follows the factor of energy increase γ^2.

We can imagine a more realistic picture of an accelerator operating on this principle. Assume, for instance, that the primary particle of mass M_1, moving at high speed, consists of bunch N_1 of particles with mass m_1. The secondary particle at rest consists of bunch N_2 of particles with mass m_2.

For such a system of particles the conditions should be observed such that the total mass of the flying bunch is much greater than the mass of the bunch at rest. Here, naturally, additional conditions arise for the bunch size. These conditions should ensure head-on collisions.

Usually, when discussing the interaction of particles, an additional notion of the impact parameter is introduced, i. e., the smallest distance between the particles at the moment of collision. In case of head-on collision, the impact parameter characterises the maximum particle approaching. For this condition to be true for bunches, their parameters should be smaller than the impact parameter. The impact parameter, naturally, depends on the relation between the masses and charges of bunches, since the impact parameter for bunches is the actual distance between them in the second phase of the impact.

If the bunches for impact acceleration are chosen properly, it may be considered that the mechanism of impact will remain the same as that for individual particles. Otherwise a fraction of the impact energy will be redistributed inside the bunch itself making the impact mechanism more intricate.

In order to understand what transfers of energies are meant here, let us consider an example. Let the colliding bunch comprise electrons with $\gamma = 100$; this corresponds to an energy of electrons of about 50 MeV. The bunch at rest consists of protons. If all the conditions for masses of bunches and for the collision parameters are observed, the bunch of ions after the collision would gain an amount of energy equal to 10 000 GeV. This figure seems fantastic even now, provided that an absolute number of particles concentrated in the primary bunch should be very great, even for a very short period of time. This circumstance presented the main difficulty in the realization of the idea. Nevertheless, big strides have already been made in this direction. Below we shall dwell on the evaluation of the possibilities of the method in question.

V. I. Veksler forsaw one of the ways of realization of impact acceleration in transition to neutral bunches – *plasmoids* which are being polarized accordingly by the external field at the moment of their collision. He examined the possibilities of plasmoid acceleration and discribed one of its mechanisms in his paper at a conference in Geneva.

Radiation Acceleration of Quazi-Neutral Bunches of Particles

Quazi-neutral bunches containing approximately equal number of particles with charges of opposite signs can be used in order to by-pass the difficulties in creating a charged particle bunch and compensating the Coulomb fields.

If we examine the mechanism of interaction of such a bunch with a flat electromagnetic wave, it will turn out that an electron riding this wave is acted upon by a force directed along its propagation. (This phenomenon has been long known and is called *Thompson scattering.*) The force acting upon one electron is proportional to the wave electromagnetic energy density and is so negligible for technically obtainable densities that it cannot be used for effective acceleration of particles. But if instead of one particle we have a bunch of them, with all the conditions of coherency being observed, then this force can be multiplied N times just as in all other coherent methods. The acceleration efficiency for a bunch of particles becomes so great that we can speak about accelerators operating on such principle.

Of all the suggestions made by V. I. Veksler, this last one turned out to be the nearest to realization. The author thought likewise. Although there were questions requiring theoretical and experimental checking, this suggestion differed from the previous ones by the fact that it envisaged the use of neutral bunches for acceleration and it seemed that upon its realization the problems of stability would not be so accute. Moreover, the 1950's were the years of the rapid development of the physics of plasma and the problems of obtaining plasma bunches had, in the main, been solved.

These were the factors that predetermined the development of the coherent methods of acceleration. Works have been started for realization of the new methods at the Lebedev Institute of Physics of the USSR Academy of Sciences in Moscow and later on at other physics centres. The experiments

that followed revealed that micro-instabilities of various types developed in dense plasma which disturbed acceleration mechanism. Radio-waves used for bunch acceleration have been unusually absorbed by the bunch, while the bunch itself generating accelerated particles was deformed significantly in the process.

The main conclusion drawn from these experiments was that this acceleration mechanism can be used for bunches of average density and that the construction of an accelerator with an energy of the order of 10 MeV is a reality.

How the coherent acceleration methods are to be realized? At the beginning of the 1960's the works on realizing the coherent acceleration methods in practice were started in Dubna under the guidance of V. I. Veksler. It was then that the decisive step was made – that of rejecting the coherency. A step that seemingly cancelled all the suggestions of the fifties. However, it turned out, that it did not. One suggestion out of all – that of *collective interactions* – had to be put into use. Here is a simple example to clear the picture for you.

Assume there is a bunch of electrons injected into an external field. The bunch is being accelerated by it and the force acting upon one particle is therewith independent of the number of particles in a bunch. The size of the bunch is unlimited.

Inject into such a bunch a heavy particle with an opposite charge (Fig. 11). The Coulomb forces generated by all the electrons strongly hold this ion inside the bunch. These forces are the stronger, the greater the number of electrons. Hence, the name collective forces, collective accelerator.

Inject such a bunch with an ion into an external field. Everything remains as it was: light electrons increase speed in the external field. What happens to the ion? It is acted upon by an internal field – the field of electrons which makes the ion move at a speed equal to that of the bunch. But the ion is a heavy particle and for it to move with the same speed as the electron it must have the energy many times greater. If, say, it is a proton, the relation has to be of an order of 2000. The internal field of the bunch made the ion move with such an energy. Therefore, if the relation between the number of electrons

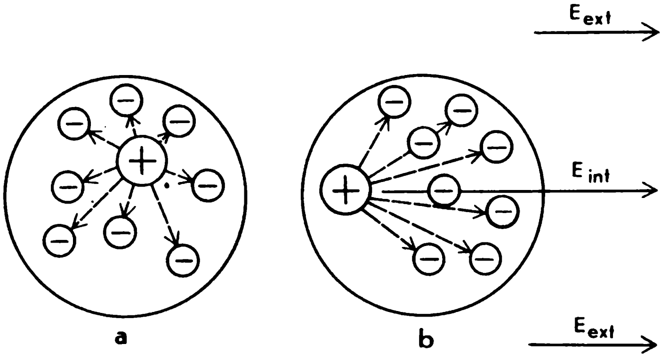

FIG. 11. Diagram showing the principle of acceleration based on the collective modes of interaction: (a) without an external field action; (b) with a two-component bunch placed in an external field

and protons in a bunch is chosen correctly the acceleration efficiency for protons can be increased 2000 times. This has become the starting point for the new method of particle acceleration.

But this did not as yet resolve all the difficulties in accelerator construction. It was clear we had to learn how to obtain a bunch with a stable charge. This boiled down to the fact that the forces in this two-component system have to be compensated while the charges not. It means that the components comprising a bunch should be in different, say, kinetic states and the equilibrium should be dynamic.

Approximately this course of reasoning made the designers speak about a ring bunch. Static equilibrium was not adequate here, because to obtain it the same number of charges of the opposite sign had to be injected into the electron bunch. In case of ions, the bunch mass and, therefore, its acceleration in the external field was determined by the total mass of ions and there was no energy gain. Interaction with the external field remained to be vague.

The works of Benett which by that time had already been substantiated by G. I. Budker again came to light. It followed from them that the Coulomb forces of repulsion in an electron beam fall off as γ^2. Therefore these forces may be compensated if a small number of ions is added.

The electron energy remained to be a parameter by varying which both the conditions of compensation of forces and the number of ions in a bunch necessary for ensuring the highest acceleration efficiency could be achieved.

Thus for a beam of electrons with a relatively low energy of about 10 MeV the Coulomb repulsion forces will be weakened 400 times due to magnetic attraction. To compensate for a deficiency of 1/400 of the Coulomb repulsion force a small amount of positively charged ions $N_i = \frac{N_e}{\gamma^2}$ may be added into such a beam consisting of N_e electrons.

To make the bunch compact electrons should be made to circulate in the closed, say, ring orbits, so that they flow round the ions travelling inside the ring. Thus a ring bunch may be obtained in which electrons move with relativistic speeds while ions fill the electron ring uniformly.

Place such a ring into an external electric field (Fig. 12). The ring begins to move in the direction of the action of the field, and the field force will act on the electrons and ions in opposite directions. But the ions also experience the attraction force on the part of the electrons.

If the number of electrons in the ring is sufficiently great, the force is prevailing and the ions begin to move in step with the ring. The effective accelerating field acts upon the ions the stronger, the greater the number of electrons and the smaller the radius of the ring cross section. Hence follow concrete requirements on plasma for obtaining highly effective field intensities. In order to increase the effective field intensity produced by electrons, and, hence, the accelerator efficiency as a whole, either the number of electrons have to be increased or the ring cross section diminished.

The appropriate calculations were made to begin the experiments.

Now a concrete method of producing a bunch had to be selected. Electrons may be injected directly into a magnetic field. By varying the magnitude of the field a ring formation may be obtained. But if the maximum value of the electron fluxes produced by modern accelerators

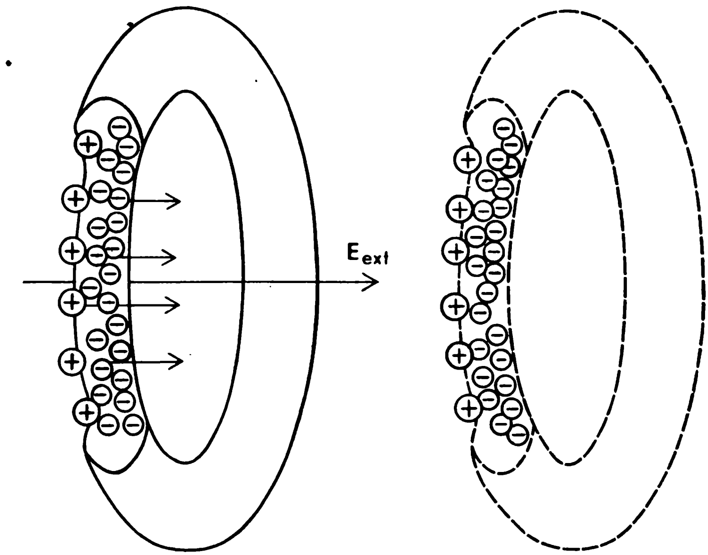

FIG. 12. Movement of a two-component ring in a collective accelerator. As in the case shown in Fig. 11 an internal field arises which confines an ion within the ring

and the sizes of the ring formation cross section in the magnetic field are taken into consideration it will turn out that the maximum intensities of the field acting upon the ion shall not exceed 100 kV/cm. For the field intensity to be raised sufficiently, the size of the ring has to be decreased. The ability of the electron formation to vary in a magnetic field with growing intensity both the radius and the size of the cross section can be used for this purpose.

A model installation was built exactly on the basis of this method. The first experimental data proved the correctness of the principle and showed that a ring capable of accelerating with satisfactory efficiency can be formed in an increasing magnetic field. It was decided to build a model in which the acceleration principle as a whole could be tested. The model was built and the first data obtained in 1967.

Electrons injected into a magnetic field form a ring about 1 m in diameter. The magnetic field is formed just as in a conventional accelerator to ensure both the confinement of electrons at the injection energy and their stable orbital travel. Ring compression occurs with the magnetic field growth. As the magnetic field increases, the ring contracts, its radius and cross section being decreased respectively: in the final state its diameter shrinks to 10 cm and its cross section to 2-3 mm.

At present, rings with an electron current of the order of several thousand amperes, have already been obtained and in the near future the current in them will amount to about several tens of thousands of amperes. The effective field intensity acting upon the ion travelling in a ring will reach tens of million of volts per centimetre while the maximum effective field intensity in the effective accelerators does not exceed 500 kV/cm.

What the collective accelerator will look like?

An accelerator should comprise of an electron injector or gun, a chamber, where the ring bunch is formed and a system for its acceleration. As was shown above, a sufficiently intense beam of electrons of already relativistic energies has to be injected into the magnetic field to obtain a dense electron ring. Therefore, an electron accelerator is required capable of accelerating with each pulse hundreds of amperes of electron current.

An analysis shows that at present an induction linear accelerator alone can do the job. Such an accelerator is a series of a single-turn pulse transformers whose primary winding is supplied with voltage pulses from special pulse modulators, an electron beam being its secondary winding. Such a system enabled us to obtain electron currents of hundreds of amperes. The accelerated electron beam arrives into a chamber where a magnetic field of an appropriate configuration is set in.

Exactly from this moment the magnetic field in the chamber begins to increase, while the size of the electron ring to diminish. Ions are being injected into the ring at the final state of the compression. For this purpose, a gas valve is being opened for a moment to let the gas into an area of an electron ring. The gas ions

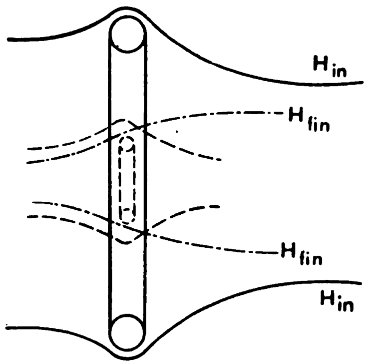

FIG. 13. Potential well of a magnetic field in which a ring is situated. Dotted line shows the stages of ring contraction and extraction and the corresponding change of magnetic field configuration

should be accelerated. The collision of ring electrons with gas molecules produces ionization and the ions obtained are trapped into an electron ring. Thus there is no longer need for special ion sources. The required ion concentration can be obtained by regulating pressure inside the gas source. Well, the bunch is ready, but we still cannot extract it from the chamber.

The above-described property of the ring to contract with the increase of the magnetic field comes into force when the configuration of the field is such that it can compensate the repulsive forces acting inside the ring before ions are being injected.

Graphically this field represents a typical potential well the bottom of which coincides with the middle plane of the chamber (Fig. 13). Such a field holds the ring. To repulse the ring the configuration of the field needs to be changed.

As is known from the theory of particles movement in a spatially heterogeneous magnetic field, a ring formation similar to the one we have, when being injected into a spatially heterogeneous field, begins to move in the direction of the field decrease. The speed of the ring will increase in step with the decrease of the azimuth

speed of electrons, i. e., the field falling along the ring axis assists the "pumping" back of the rotational energy into the longitudinal motion energy. Thus in order to impart to the ring as a whole motion along its axis, it is required both to eliminate the potential barrier and to generate the magnetic field decreasing along the axis. It should also be borne in mind that the field gradients should not create such accelerations at which ions may tear away from the ring due to inertia.

For the removal of the potential barrier and the extraction of the electron ring a special device has been developed which ensures the change of the configuration of the magnetic field at the final moment of contraction of the electron ring and restores it for the next cycle of formation of a new ring.

Now comes the stage of ring acceleration. The initial acceleration of the ring can be ensured by selecting the corresponding time for switching-in the additional turns. In the accelerator mode described above the acceleration continues until the speed of the ring equals 0.3 that of light. It is impossible to accelerate particles to greater speeds in such a way since the store of kinetic energy of electrons is limited.

In order to continue acceleration this energy has to be supplemented from the external sources so that the energy of the translational motion increases while the rotational energy remains unchanged at least on an average. This may be achieved by placing a ring bunch into an external electric field. When selecting the method for setting-in an accelerating field, certain specific features of acceleration for such a bunch have to be taken into account.

The ring is a compact formation with a great charge and an intrinsic ring current. A considerable energy of the external field required for its acceleration creates additional difficulties in designing such an acceleration system. Such a dense formation of charges forms a sufficiently powerful electromagnetic field around. A fraction of this field may radiate into space. It is necessary that the energy radiated by the ring does not exceed the energy obtained from the external field. And, finally, the presence of ions in the ring also limits the intensity of the external

field. A high-frequency cavity used as the main accelerating element was a cylinder the dimensions of which were chosen so that the time of the ring flight through it was less than the period of intrinsic oscillations of the electromagnetic field. It is a fact that cavities of various types are used in those accelerating systems where the energy of the high-frequency field has to be stored to be imparted to the accelerated particles at a proper moment. In our model the energy of the high-frequency field should be stored beforehand to be imparted to the ring in the process of acceleration.

Calculations show that the energy stored in the cavity can be used for acceleration of bunches with the number of particles equal to 10^{14}. This ensures the accelerating field inside the bunch of the order of 10^7 V/cm. Detailed examination, however, reveals certain contradictions. On the one hand, the conditions of energy supply demand that maximum amplitudes of the electron field should be obtained in the resonator, and on the other hand, there are limitations on the accelerating field. In acceleration of a ring-shaped bunch large inertia forces trying to break heavy ions away from the electric ring act upon them. At certain intensities of the electric field the internal forces will be inadequate to compensate for the inertia forces and the ions will lag behind the electron ring.

In order to obtain a greater ion energy, it is necessary to lengthen the acceleration path and, hence, to increase the number of cavities placed along this path. The design features call for the creation not of a solid unit but of a set of uniformly spaced cavities. As a result the mean intensity of the external field becomes several times less than the one described above. This leads to a decrease in the acceleration efficiency of the entire system. A combined system is being built to bypass these contradictions.

The process of acceleration will run as follows: we have seen above that when the ring moves through the field decreasing in the direction of its propagation the energy of the rotational motion transforms into the energy of the translational motion. An opposite transformation of energy, naturally, occurs in the magnetic field increasing along its propagation. Now let us examine the system using

the specified properties of the decreasing and increasing magnetic fields in combination with the system of accelerating cavities. Let there be a sequence of cavities and gaps without an external electric field. Let us create in the gap between the cavities a longitudinal magnetic field falling according to the linear law and inside the cavities, a field increasing to the former values. Then in the gap between the cavities the ring is being accelerated under the action of the falling off magnetic field so that the acceleration value does not exceed the permissible values and the speed of electron rotation inside the ring decreases. Inside the cavity itself both the magnetic field and the electric field act upon the ring provided that its energy is being expended both on direct acceleration of the ring and on restoration of the speed of the rotary motion of electrons in a bunch lost at the previous region. For this condition to be realized the intensity of the electric field should be several times greater than the permissible one. Therefore, the magnitude of the energy stored in the cavity should also be sufficiently great.

There is no need to prolong the system of cavities to the end of the accelerator. The electrons, actually, have already played their role: they have imparted to the ions the required energy. They had for this purpose sufficiently great energy of the rotary motion. Now they can expend this energy on imparting to the ions the translatory speed having travelled two thirds of the accelerator length without cavities and without an electric field but with a falling off magnetic field in which, as we already know, the bunch is accelerated further due to the rotational energy of the electrons themselves.

When regarding the system of ring acceleration, it was considered that the accelerating field remained constant along the entire accelerator length and that it was selected depending on the conditions of ions retained inside the ring. But the dimensions of the ring bunch should therefore remain constant or even decrease.

Therefore a special system for keeping the size of the ring bunch within the required limits should be provided. The ring radius as well as the radial size of its cross section are retained by the constant magnetic field in which

the ring moves. Therefore, the task of keeping the size of the ring bunch boils down to the task of retaining the longitudinal size of its cross section. Such tasks are being solved in many accelerators of charged particles and some methods could have been applied in the collective accelerator. But all these methods require the creation of complex and costly high-frequency systems.

The characteristics of the ring bunch enable us to use a more economic and simple system which, actually, can hardly be called a system. That is, the use of the intrinsic field of the bunch for the purpose of focusing.

The idea of using the bunch intrinsic field for its focusing arose when the effect of metal shields on the electric fields had been studied. When a bunch of charged particles moves along a metal surface an electric field appears between the bunch and the surface. The character of the distribution of this field may be pictured if we mentally remove the surface but retain the mirror image of the bunch produced by this surface but already with an opposite charge.

Let us consider a simple example: a straight charged pinch formed by moving electrons is shielded by a conducting metal plane. If the distance from the centre of the pinch to the surface is considerably greater than its cross section, then the mirror image will be an infinitely thin pinch formed by the oppositely charged particles, as is evident from Fig. 14. A simple examination of the forces of interaction between the "mirrored" pinch and the extreme particles of the real one shows the effect of the focusing force on the extreme particles of the bunch directed toward its centre. The magnitude of this force is considerably smaller than the forces of the Coulomb repulsion of the pinch at rest. However, in longitudinal movement the above-described relativistic factor γ operates once more: the intrinsic repulsive forces fall off γ^2 times and a possibility of compensating them by the image forces appears.

Of course, the actual picture corresponds but little to the examined one. It has alredy been noted that the most important factor operating inside the real ring is the existence of the two mutually perpendicular movements: the movement of electrons around the orbit and of the

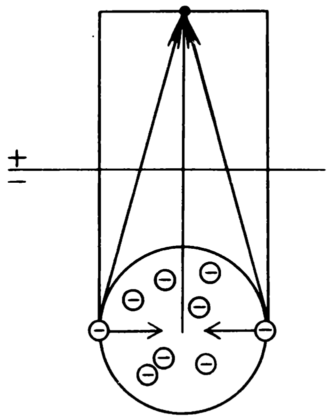

FIG. 14. Diagram of interaction of electrons bunch with the shield. The extreme particles are acted upon by the forces directed towards the bunch centre, i. e. focusing forces

ring as a whole. The presence of these movements considerably changes the picture of the image. The introduction of translational motion leads to the fact that the interaction with the image becomes not only electric but also magnetic. This, as in the case of a ring, brings about a γ^2 time decrease in the forces of interaction with the image. Therefore, a conventional metal surface is not fit for use in focusing.

For the reasonings about the charged pinch to hold, the surface should reflect the electric field of the bunch and let its magnetic field pass through without reflection. Such surfaces do exist. The simplest example is a metallic tube with slits along the movement of the ring placed between the cavities.

We have examined all the elements of a future accelerator for super-high energies ensuring a high gain of energy per unit length of the accelerating system. Today a model of such an accelerator has already been built and the validity of the basic principles of the new accelerator has been demonstrated (Fig. 15). However paradoxal acceleration efficiencies of the order of 60 MeV/m have already been obtained on this far from being perfect model

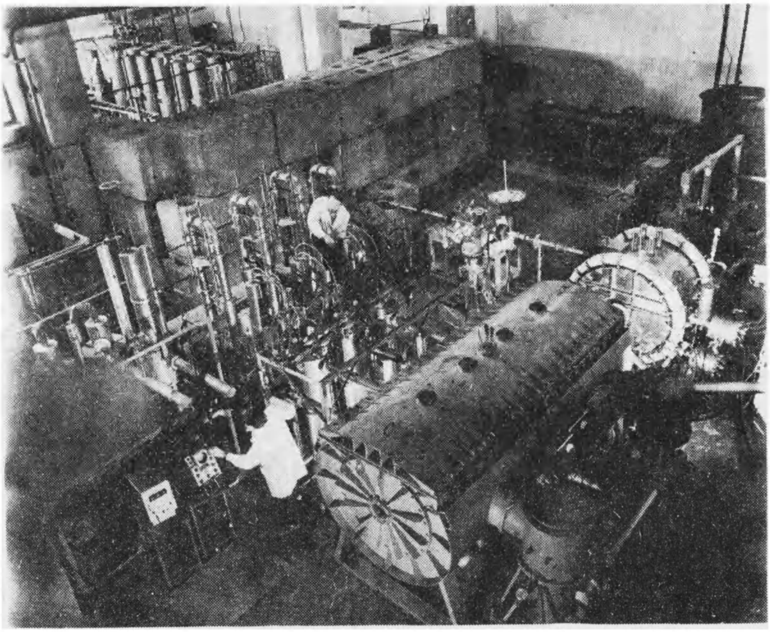

FIG. 15. Electron ring accelerator at Dubna used for testing a new method of particle acceleration

constructed by half-homemade methods. This efficiency already exceeds that of synchrophasotrons.

At present the construction of an installation is under way in which the accelerating efficiency will be boosted several times. It will serve as a prototype of accelerators of the future (Figs. 16, 17, 18).

This accelerator has another specific feature. Speaking about ion accelerators, we mentioned nowhere what kind of ions they used. Usually these were protons. Collective accelerators may use any kind of ions. The accelerating process does not actually depend on the kind of ions. This opens up absolutely new possibilities in nuclear physics.

However the main guide-line in the research for the next few years will be the selection of the most rational system of particle acceleration up to super-high energies.

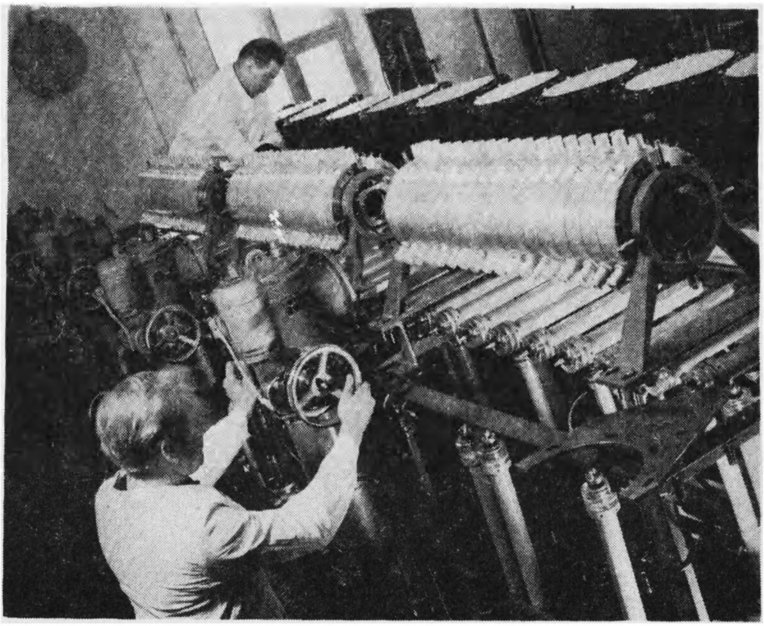

FIG. 16. Assembling an electron accelerator capable of accelerating electron currents to 2000 A

The two variants of such systems are shown in Figs. 19 and 20. The work at the design of such an accelerator is still going on. The time has come to ask whether the specific features of this accelerator, if any, will be advantageous in conducting physical experiments.

Although this question is still being studied, we can already speak about certain specific features of this accelerator and its advantages. We have spoken in the main only about the energy of the accelerated particles and also about the possibilities of attaining its ever higher values. But this is only one side of the question. Other beam characteristics, such as intensity, geometrical configuration and time structure, play an important role in conducting physical experiments effectively.

The main distinctive feature of the collective accelerator beam from the "classical" one lies exactly in its time

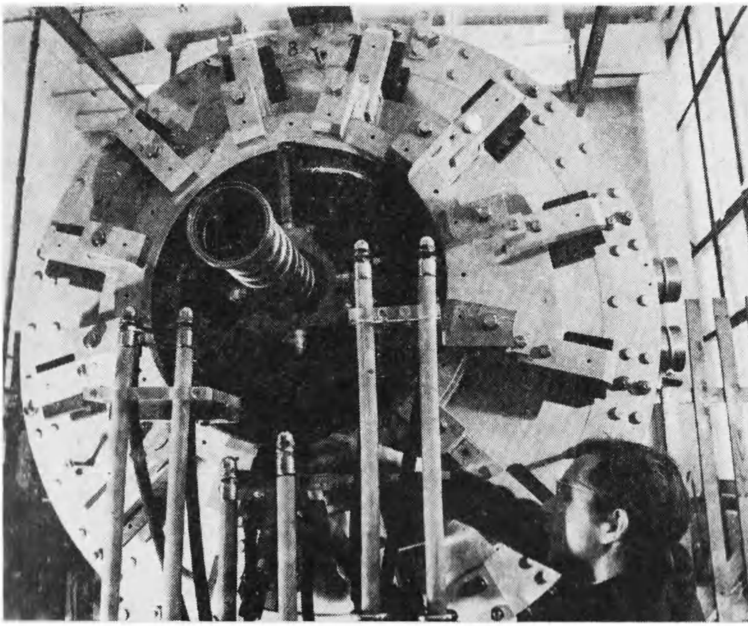

FIG. 17 The main unit of a new accelerator the chamber in which ring plasmoid is formed

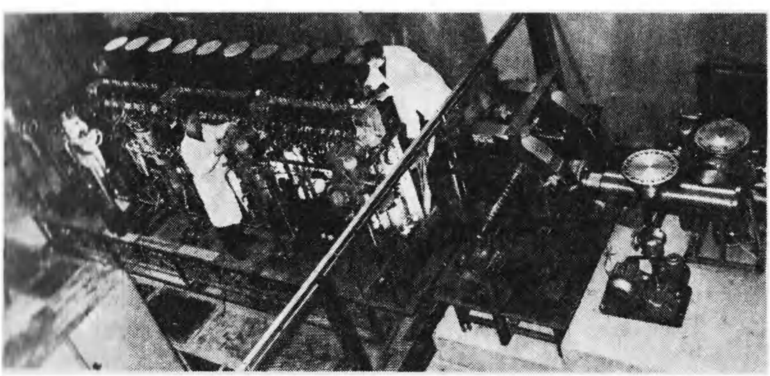

FIG. 18 General view of the first "accelerator of the future" — a col- heavy-ion accelerator now being built at Dubna

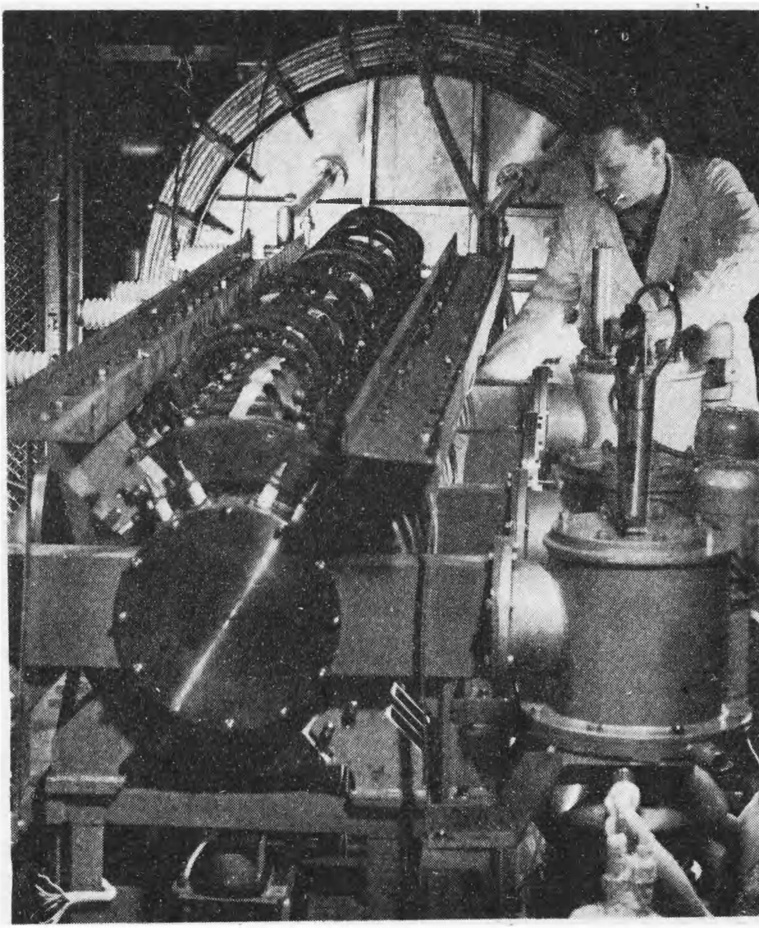

FIG. 19. The first experiments in accelerating ring plasmoids

structure. As we have seen above, the ions are being accelerated in the electron ring, the sizes of which along its travel are rather small. As a consequence, the time of the interaction with the target is about 10^{-11} s, while in conventional accelerators it makes up fractions of a second or is continuous.

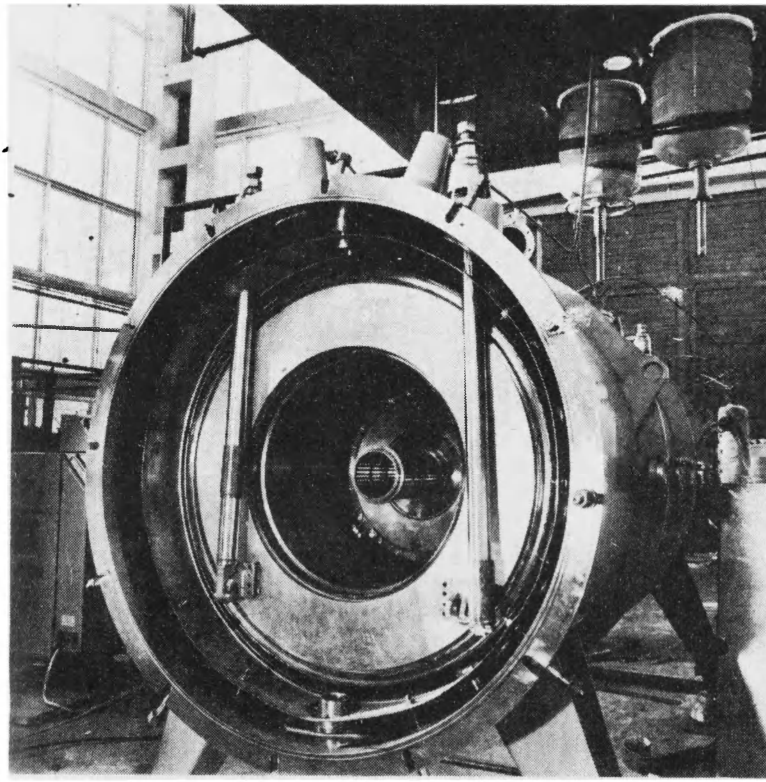

FIG. 20. Superconductivity is also used for the collective accelerator. Section for accelerating electron rings with the use of a superconducting magnet

Is it possible to use such beam peculiarities effectively? Let us consider them as applied to various types of accelerators. The collective method of particle acceleration is a universal one, in other words, it is good for various types of accelerators. These include a multi-charge heavy ion accelerator which can be used instead of a cyclotron or linear accelerator, or a heavy-current proton accelerator for energies of the order of 1 GeV replacing costly meson

plants or, finally, proton accelerators with energies 10-100 times exceeding those of present-day accelerators.

The synthesis of the new elements of the Mendeleyev Periodic Table is one of the main problems which is being worked on today in the heavy ion physics. If we compare the Periodic Table of today with what we had twenty years ago we can see that dozens of new elements have been added to it some of which named after prominent physicists of our generation.

The recent entries were made by Soviet scientists. The last element numbered 105 appeared in 1972. (At present, the birth of the 106th element has been declared.) Its synthesis became possible owing to the creation of heavy ion accelerators. A conventional cyclotron or a linear accelerator was specially adjusted to a synchronous acceleration of nuclei with a definite charge-to-mass ratio. The nuclei with such a ratio were obtained directly from specially designed ion sources. But conventional cyclotrons could accelerate only those nuclei which subordinated to this ratio. There were but a few of such nuclei and they all occupied places at the beginning of the Periodic Table, in other words, they were relatively light. Such nuclei were accelerated and targets made from heavy elements such as, for instance, uranium were bombarded by them. Then, along with other possibilities of interaction, a possibility of fusion of a light accelerated nucleus with a heavy target nucleus arouse. For such a fusion to occur, the bombarding nucleus should have a certain energy – the fact that restricted the possibilities of accelerating various nuclei in a cyclotron.

That was where theory came into play. The thing is that all heavy elements are unstable and subjected to various decays. However, the character and the time of decay differ for different elements. One of the tasks the theory had to solve was to find out what kind of a decay is to be expected in a new element. Further experiments depended on these forecasts. Researchers sought for forecasted radiators in the targets and measured the time of decay of the new nucleus. To avoid mistakes, basic chemical properties of the new element were also studied. In case these properties coincided with those forecasted by the Periodic

Table the new element was considered to be found. Just to have an idea how difficult these experiments were, it is enough to say that they all were conducted with a veritably few number of atoms. That was how the new elements were discovered. And each new element was discovered with an ever greater difficulty. The lifetime of these elements diminished. Then the theory prepared a surprise. It stated that this phenomenon is temporal and that the following elements will have a longer lifetime. What is more, it insisted that, for instance, element 114 is a stable one within the lifetime of a human being.

So we had to forget for the time being the unstable elements and to deal with those which have already been perceived and not to examine only the properties of the decay. This is where the shortcomings of the cyclotrons manifested themselves.

How can we accelerate heavier elements? Numerous suggestions were made in various countries. They all boiled down to the fact that two accelerators have to be used in succession for the purpose. Heavy ions of, say, xenon, are taken and the cyclotron is adjusted at a definite ion charge-to-mass ratio. After acceleration in the first accelerator by stripping the electrons, the charge-to-mass ratio increases at the intermediate target so that the acceleration in the second accelerator makes the total energy of the ion sufficient for conducting synthesis of the elements.

This acceleration scheme for two cyclotrons is already in operation in the Soviet Union. However, the experiments have not as yet yielded the expected results because the intensity of accelerated ions is rather low mainly owing to losses of particles during electron stripping. In order to obtain elements further, the intensity should be boosted at least 100 times. The collective accelerator presents just such an opportunity. But the use of the collective accelerator with its configuration of the beam of accelerated particles enables us to change the experiment procedure of obtaining new elements.

Perhaps we can measure the speed of the newly obtained super-heavy nucleus? Up till now such measurements were not made since it was impossible to fix the time of the birth of a heavy nucleus in a continuous cyclotron beam

In the new accelerator all ions interact with the target at one and the same time with an accuracy of up to 10^{-11} s. The moment the beam hits the target can therefore be taken as the beginning of time reading. If a heavy ion is found at a certain distance apart from the target, its speed can be determined by the time of its flight.

True, the knowledge of speed alone is insufficient for the determination of a new element. Some other basic parameter of the moving nucleus, for instance energy, has to be measured simultaneously. It is a fact that an ion passing through a substance loses some of its energy on ionization. These losses depend on the ion energy, which can be determined by measuring the former. Nuclear physics has an instrument, called *ionization chamber* for taking such measurements. Lately high-speed tracking devices have been developed which can measure full ionization (proportional chambers). The mass can be easily defined from the known values of energy and speed. Thus the new accelerator makes it possible not only to conduct at an increased intensity all the experiments in searching for and obtaining new elements but it also opens up absolutely new experimental opportunities based on direct observation of the path of the newly-formed nucleus.

Most unique physical apparatuses are used for conducting research into high energy physics. Its cost is sometimes comparable with that of an accelerator, therefore, it is most important that the high-energy particle accelerator presented opportunities for conducting experiments opening up ever new mysteries of nature by more accessible and simple methods.

Does a collective accelerator possess such properties? The collective accelerator is already unique because higher energies of particles with greater intensity can be obtained in it. We can already speak of an accelerator capable of producing 10^{14} accelerated protons per second, which is about 100 times in excess of what had already been obtained in a synchrophasotron. This means that we can speak about absolutely new physical experiments.

The main experiments on the accelerators are being conducted with secondary particles, in other words, with

particles that are obtained as the result of interaction of the primary beam with the target. This interaction gives birth to a great number of most varied particles; among them there are such particles the study of which presents great interest to physics. The task is to separate these particles with the help of various separators. In high-energy accelerators they are high-frequency systems.

Now let us get acquainted in general terms with the operation of such a system. Assume particles with various masses flying in one direction. One of them is of interest to physics, and its interaction has to be studied. Another particle should be detained from getting into a registering apparatus so that the products of its interaction do not spoil the general picture of the interaction of the first particle. Such particles have to be separated in space. Such a separation is quite possible since their interaction with the external field differs owing to difference in their masses. In high-energy accelerators high-frequency fields of cavities or waveguides are used for this deflection. The best results of the external fields action on the particles are obtained when their interaction with the cavities takes place in different half-waves of the field oscillations in the cavity. Then the deflection effect is maximum. Therefore at the first stage the separation of particles in space is conditioned by their separation in time of the oscillations. To avoid mix up of particles of a beam during their separation in time, the primary beam is subjected to the action of the high-frequency field so that a sharp beam modulation is being observed at a frequency of the applied field. The beam comprises separate bunches separated by empty space. Such a temporary structure is also retained in a beam of secondary particles.

The action of the separator boils down to the fact that the required particles shift to non-occupied regions owing to the interaction with the field. Further on such a phase redistribution can be easily turned into space separation of particles with the help of the external fields. To do this the length of the electromagnetic wave of the deflecting device should correspond to such a structure of the beam. It is evident that the process of particle separation is a very complicated one.

After examining the process of separation the advantages of the collective accelerator become quite evident. While in conventional accelerators the spacial structure of the beam should be specially formed for particle separation, in collective accelerators the structure is formed by the accelerator itself in the best possible manner. This circumstance allows to perform fusion of high-energy particles of equal lengths or to use essentially shorter channels for one and the same energies. The last circumstance is very important for the study of particles with short lifetime. It becomes possible to study the properties of such particles which escape in conventional accelerators before reaching the experimental apparatuses. We shall not examine here all the experiments possible on the new accelerator since it would detract us far from the problems being discussed here. We shall only examine one direction of research into high-energy physics – research into neutrino.

Neutrino is, probably, the most mysterious of all elementary particles. The discovery of this particle enabled us to explain most entangled phenomena of the microworld. Today, too, physics bank their great hopes on it. But the research into neutrino seems to be the most difficult field in the physics of elementary particles, since the requirements here towards accelerators are sometimes too excessive.

Neutrino practically does not interact with matter and, therefore, to obtain sufficient data in reactions with neutrinos fluxes of these particles should be sufficiently great. The intensity of a collective accelerator enables the researchers to obtain such fluxes. Moreover, as distinct from the existing accelerators in which to boost the neutrino intensity the particles of all energies are directed to an experimental installation, which makes it impossible to conduct a number of experiments, the collective accelerator due to its great intensity enables us to carry out the experiments with low-energy neutrinos. Such experiments may shed light on the nature of weak interactions.

Even the most cursory examination of the new possibilities which the collective accelerators open up for nuclear physics shows that physicists are in great need of such accelerators. A question naturally arises: if the variant of the

accelerator examined is the only one or there are ways of improving and developing the collective method? Evidently this question has two aspects. Thus, high cost of modern accelerators served as an initial precondition for the development of the new methods of acceleration, the collective one in particular. Therefore, one aspect of the question is to find the cheapest methods reasoning from the known principles of acceleration.

The cost of the accelerating system, which taken to pieces consists of a system of single cavities, makes up the main cost of the accelerator. The acceleration takes place in high-frequency fields. However, it is known, that a unit of energy stored in a high-frequency field is hundred times more expensive than the same amount of energy stored in a conventional capacitor. Therefore, a system comprising a series of ring-type capacitors would have made it possible to obtain accelerated particles by a cheaper method.

The only difficulty is that the field in such capacitors should be created only for the time of the ring flight through the capacitor; and this time is very insignificant (of the order of 10^{-10} s). This can be achieved only after a corresponding development of the pulse technique.

Future possibilities of the development of this method is another aspect of this question. Such a development should, naturally, lead to a further increase in the efficiency of the accelerating process. If we examine the expression for the efficiency of the field acting upon the ion from the side of electrons, we shall see that the intensity can be raised either by increasing the number of electrons in the ring or by decreasing the size of the cross section of the ring bunch.

Let us dwell only on one possibility. It is a fact that a sufficiently intense electron beam is compensated by ions so that $N_i \geqslant N_e/\gamma^2$. In addition to rotational motion electrons in the ring also oscillate within the bunch cross section.

With time a fraction of the oscillatory motion energy is expended on radiation in a magnetic field. Due to magnetic compression the beam cross section diminishes owing to the energy losses on radiation in a lateral travel of particles. The section diminishes as long as the collision of particles comes into play. A stationary state sets in – a relativistically

stable beam which we speak about already in connection with Budker's suggestion. Such a stationary state sets in the collective accelerator with the radius of the ring cross section being equal to 10^{-3}-10^{-4} cm; the intensity of ion accelerating field may reach therewith 10^9 V/cm. It means that giants may shrink to table devices.

But this is all fantasy so far. Today a large amount of research work has to be conducted which will make it possible to develop a high-energy accelerator with the best possible acceleration efficiency.

Having read the last section of the booklet, the reader is, undoubtedly, ready to accuse me of the partial attitude to the collective method of acceleration. I also thought so when I read over my work. But it can easily be explained by the fact that I am really partial in the first place, and in the second place, there has been so little said in popular literature about the new method of acceleration that I regarded my main task in showing what kind of an accelerator it is, its outstanding features as compared with those that are in operation today. Nevertheless, for fairness sake, I shall tell about the difficulties which have to be overcome on the way to its creation. In order to make such an accelerator considerably more efficient than the synchrophasotron, the electron ring should necessarily contain a great number of electrons. The figures cited above relate to the number of electrons of the order of 10^{14}. At present, we are able to obtain rings with the number of electrons of the order of 10^{13}. Further increase in the number of electrons can be attained after numerous experiments. The main aim of the experiments is to avoid the appearance of dangerous collective fields produced by groups of particles in such dense beams, the collective properties of which are so necessary for obtaining the desired acceleration efficiency. Such fields may lead to ring destruction.

Thus, we have dwelled on the main three trends of the development of contemporary physics and technology of accelerators. We hope that in the nearest future nuclear physics will receive new installations and instruments for their research work and will make new and decisive steps in understanding of the world around us.

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A lecture for a broad readership in nuclear physics on the new principles for accelerating charged particles that may be embodied in future accelerators. Describes experimental prototypes now being developed.